Near-Infrared Spectral, Organic Carbon and Bulk-Density Changes Under Contrasting Crop Rotations in the Swartland Region, South Africa

Nompumelelo Ngejane[1], Andrei Rozanov[2], Catherine Clarke[2], Johann Strauss[3]

1 - KwaZulu-Natal Department of Agriculture and Rural Development, 1 Cedara Road, Cedara, Pietermaritzburg 3200, South Africa
2 - Department of Soil Science, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa
3 - Western Cape Department of Agriculture, Main Building, Elsenburg, Muldersvlei Road, South Africa

Corresponding author: Nompumelelo Ngejane *e-mail: ngejanen@gmail.com*
Received: 01 July 2026 *Accepted: 16 October 2026*

Abstract

Understanding how contrasting crop-rotation sequences influence soil properties is important for assessing changes in soil condition and sustainable crop production. This study evaluated changes in near-infrared (NIR) spectral absorbance and soil bulk density (ρb) between a common 2015 baseline and a 2019 endpoint in a long-term crop-rotation trial at Langgewens Research Farm. In 2015, the trial was planted to wheat as a uniformity crop, after which contrasting crop sequences were implemented from 2016 to 2019. Surface soil samples (0–5 cm) were collected from 120 experimental plots in 2015 and 2019. Samples were oven-dried, ground, and passed through a 2 mm sieve before NIR scanning, while ρb was measured using 100 cm³ cores. NIR absorbance was higher in 2019, despite an overall decline in soil organic carbon, while ρb decreased from 1.36 to 1.23 g cm^{-3}. More diverse crop sequences generally showed greater increases in spectral absorbance and reductions in ρb. These contrasting responses indicate that NIR absorbance was not directly associated with changes in soil organic carbon. Contrasting crop rotations were associated with measurable changes in soil spectral characteristics and packing, highlighting the value of interpreting NIR alongside complementary soil properties and repeated measurements.

Keywords: crop rotation, near-infrared spectroscopy, soil bulk density, soil health

Introduction

Soil properties vary considerably within agricultural fields as a result of interactions among soil-forming factors, topography, climate, land-use history, and management practices (McBratney et al., 2003; Blanchy et al., 2023). This spatial variability influences soil water dynamics, nutrient availability, root development, and ultimately crop productivity (Poggio et al., 2021). Within-field differences in soil properties may also affect the response of soils to

agricultural management, making an understanding of spatial and temporal soil variability important for evaluating changes in soil condition and crop production under different cropping systems.

Landscape position is an important driver of within-field soil variability because it influences water redistribution, erosion and deposition, and the accumulation and decomposition of organic materials. Consequently, properties such as soil texture, pH, organic matter, nutrient concentrations, and water-holding capacity may vary along topographic gradients (McBratney et al., 2003; Jakšić et al., 2021; Wang et al., 2023; Yaqoob et al., 2024). Topography-driven variability has also been associated with differences in soil carbon distribution and crop productivity within agricultural fields (Jakšić et al., 2021; Védère et al., 2022; Dhillon et al., 2025). Establishing a common baseline is therefore particularly important when assessing changes associated with subsequent crop-rotation treatments, because pre-existing spatial variability can influence comparisons among treatments.

Soil management and cropping history can modify soil physical condition over time (Blanco-Canqui and Ruis, 2018). Crop rotation, residue management, fertilisation, and tillage influence soil organic matter dynamics, aggregation, pore structure, and compaction, with consequent effects on soil water movement and root development (Ashworth et al., 2020; Rigon and Calonego, 2020; Mtyobile et al., 2020; Xu et al., 2024). Bulk density is a widely used indicator of soil physical condition because it integrates the effects of soil structure and pore-space characteristics and is directly related to soil compaction, aeration, water infiltration, and root penetration (Håkansson and Lipiec, 2000; USDA Natural Resources Conservation Service, 2022). Higher bulk density generally indicates reduced total pore space and may constrain root growth and water movement, whereas lower bulk density is generally associated with greater porosity and more favourable conditions for root development. Bulk density is also required for converting soil carbon concentrations to area-based carbon stocks, making it relevant to assessments of changes in soil carbon and soil quality (Nunes et al., 2020; Orzech et al., 2021).

Detecting changes in soil condition requires measurements that can be applied consistently across spatially variable agricultural fields. Conventional laboratory analyses provide reliable measurements of individual soil properties but can be relatively time-consuming and resource-intensive when large numbers of samples are required. Visible and near-infrared (Vis–NIR) spectroscopy has therefore received increasing attention as a rapid approach for characterising soil properties and identifying differences in soil condition (Wang et al., 2024; Win et al., 2025; Shin et al., 2025). Soil spectral responses contain information related to mineralogical, organic, and chemical characteristics and have been used to estimate properties including soil organic carbon, texture, pH, and nutrient status (Wang et al., 2023). This makes spectroscopy potentially useful for monitoring spatial and temporal changes in soil properties and supporting precision soil management.

Bulk density is not directly measured from a specific Vis–NIR absorption feature; rather, its prediction from soil spectra is generally indirect and relies on statistical relationships between spectral response and soil constituents associated with bulk density. Soil bulk density has nevertheless been successfully predicted using Vis–NIR spectroscopy when appropriate calibration and validation datasets are available (Katuwal et al., 2020). Such relationships can arise because bulk density is associated with soil properties and constituents,

including soil organic carbon and particle-size distribution, that contribute to the measured spectral response (Soriano-Disla et al., 2014). In the present study, bulk density was determined directly from intact soil cores, whereas NIR spectra were obtained separately from prepared soil samples. The spectral and bulk-density measurements were therefore treated as complementary indicators of soil condition rather than as a spectral prediction of bulk density. Consequently, differences in spectral response between sampling dates were not interpreted as direct measurements or estimates of changes in bulk density because no bulk-density prediction model was developed or independently validated in the present study.

Temporal assessment of soil properties is particularly relevant in long-term cropping experiments, where differences in management may gradually modify soil physical and chemical conditions. Crop rotation and other management practices can influence soil organic carbon, aggregation, pore structure, and bulk density over time (Rigon and Calonego, 2020; Mtyobile et al., 2020). However, the magnitude and direction of these changes depend on the initial soil condition, environmental conditions, and management history. Changes in soil properties therefore cannot be interpreted independently of their initial spatial variability. In the present study, 2015 represented a common baseline established before the implementation of the subsequent crop-rotation treatments, whereas 2019 represented the endpoint of the observation period. Thus, comparison between the two sampling dates provides an assessment of the net change in measured soil properties and spectral response over the study period. Because measurements were available only for 2015 and 2019, the study does not attempt to describe the trajectory or rate of change between these dates.

Despite the increasing application of soil spectroscopy for rapid soil characterisation, quantitative interpretation of spectral measurements requires appropriate reference measurements and calibration and validation procedures (Soriano-Disla et al., 2014). Vis–NIR spectroscopy has demonstrated potential for estimating a range of soil physical and chemical properties, but prediction performance varies among properties and depends on the quality and representativeness of the calibration dataset (Soriano-Disla et al., 2014; Katuwal et al., 2020). In particular, bulk density presents an additional challenge because the structural pore space that defines bulk density is altered when soil samples are dried, sieved, and ground for laboratory spectral measurements. Therefore, there is a need to distinguish between changes in measured spectral response and changes in directly measured soil properties when spectroscopy has not been calibrated specifically for their prediction. Assessing NIR spectral response together with directly measured soil organic carbon and bulk density provides an opportunity to describe temporal changes in soil condition while maintaining a clear distinction between measured soil properties and spectral characteristics.

The objective of this study was to evaluate changes in soil organic carbon, NIR spectral response, and bulk density between 2015 and 2019 in an experimental field subjected to contrasting crop-rotation sequences following a common baseline wheat crop. Specifically, the study aimed to (i) quantify changes in soil organic carbon and bulk density between the 2015 baseline and 2019 endpoint, (ii) characterise differences in NIR spectral response between the two sampling dates, and (iii) evaluate differences in SOC, bulk density, and spectral response among the crop-rotation treatment groups.

Materials and Methods

Study area, trial design, and layout

This study utilised data from a long-term crop and soil sustainability field experiment located at the Langgewens Research Farm in the Swartland region of the Western Cape, South Africa (33°16′34.41″ S, 18°45′51.28″ E), depicted in Figure 1. A detailed description of the site characteristics, soil properties, and experimental design has been previously reported by Ngejane et al. (2026). The field experiment was conducted within a 12-ha long-term experimental area at Langgewens Research Farm. The trial area consisted of three camps (19B, 19C, and 20) of different sizes; therefore, the experiment was established using an incomplete block design. The treatments represented contrasting crop-rotation sequences and levels of crop diversity. The whole trial area was planted to wheat in 2015 as a uniformity crop, before the contrasting crop sequences were implemented from 2016 onward. The present study uses soil measurements collected at two sampling dates, 2015 and 2019. Thus, 2015 represents the common baseline, and 2019 represents the endpoint after four years of contrasting crop-rotation management. The 2016–2018 information describes crop-management history and does not represent intermediate NIR or bulk-density measurements.

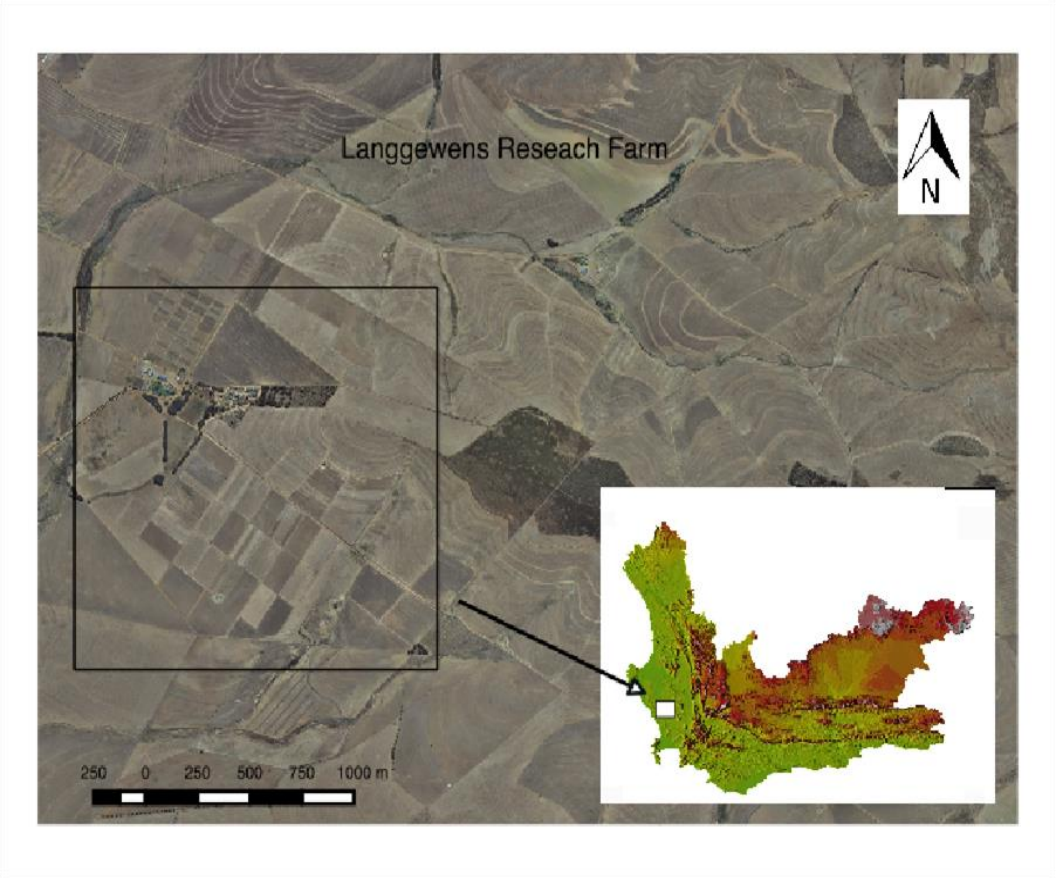


Figure 1. *Map of the Langgewens Research Farm and its location in the Western Cape province, South Africa.*

Soil sampling, preparation, and analysis

For both sampling dates, 2015 and 2019, surface soil samples were collected from the 120 experimental plots before planting. Bulk-density samples were collected from 0–5 cm using 100 cm³ metal cores. The cores were taken to the laboratory, oven-dried and weighed,

and bulk density (ρb) was calculated as oven-dry soil mass divided by core volume, expressed in g cm^{-3} (Ma et al., 2013). The soil was then ground and passed through a 2 mm sieve. The <2 mm fraction was scanned using a Bruker Multi-Purpose Analyser spectrophotometer to obtain NIR spectral signatures, following the scanning approach described in Ngejane et al. (2026). A summed absorbance index (A) was calculated from absorbance values across the measured wavenumbers (4000–9000 cm^{-1}).

This index is used here as a descriptive spectral summary rather than as a direct physical quantity representing total electromagnetic absorption. The ground samples were also used to determine soil organic carbon (SOC) using the Walkley–Black dichromate oxidation method according to the procedures of the Non-Affiliated Soil Analysis Work Committee (1990).

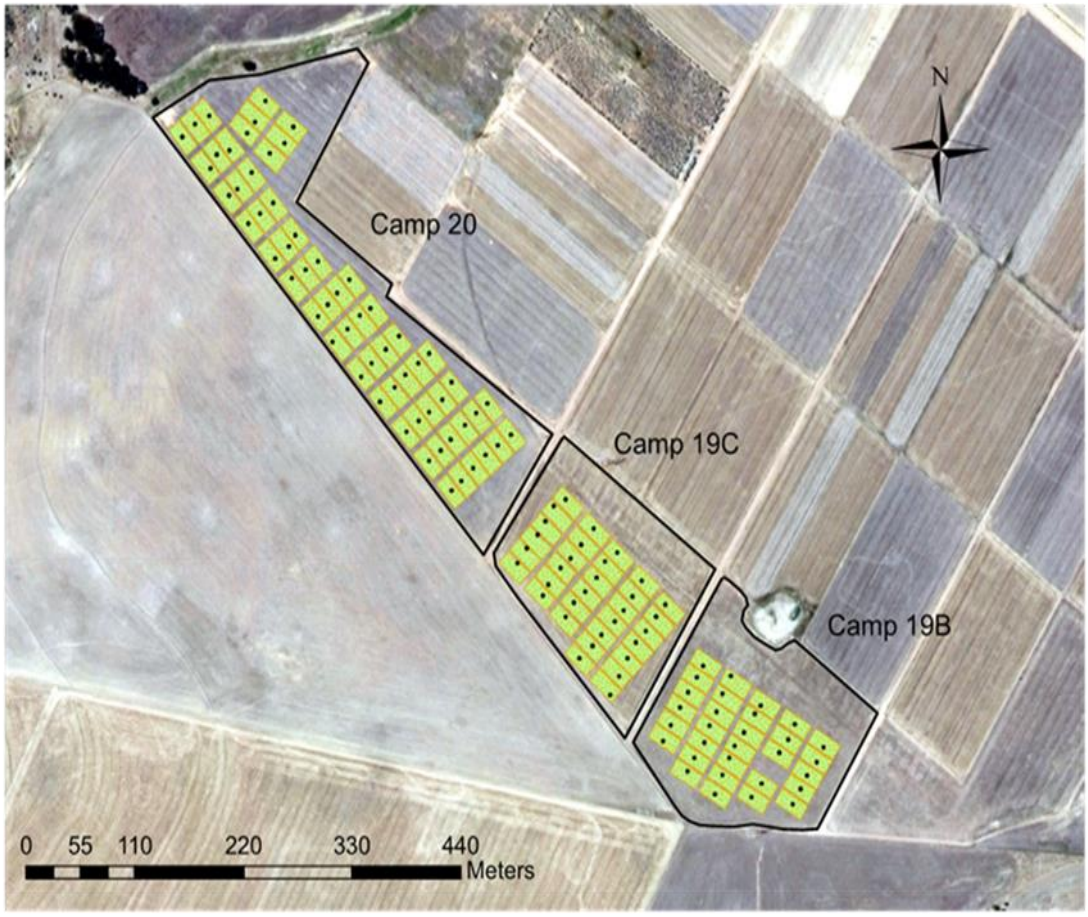


Figure 2. *Experimental plot layout per camp. Spatial points on the map represent surface sampling locations within each experimental unit.*

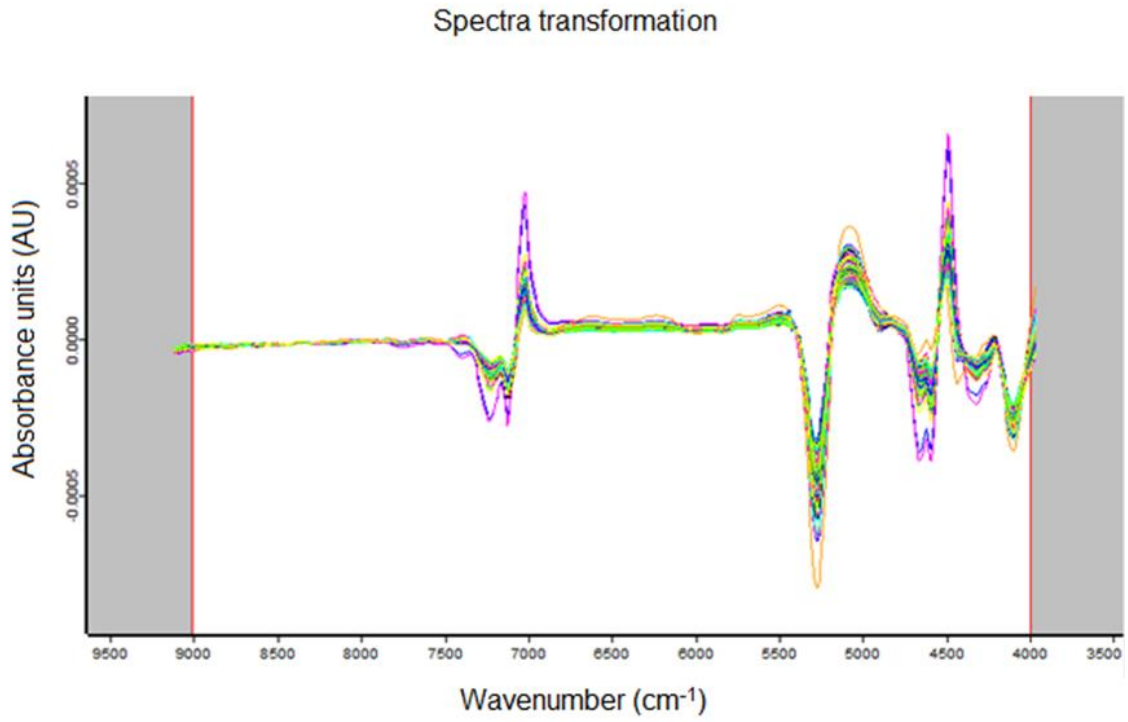


Figure 3. *Absorbance in selected regions versus wavenumbers*.

Statistical analysis

The 2015 and 2019 observations were compared at the plot level, with 2015 serving as the common baseline and 2019 representing the endpoint. The analysis employed *t*-tests for comparisons between years and treatments. Treatment effects on spectral change were evaluated using pairwise comparisons among treatment groups. The plot was considered the experimental unit, while the four trial replicates constituted the experimental replication structure. The 649 band-wise tests and 30 crop-sequence tests were considered exploratory. For the crop-sequence comparisons presented in Table 4, *p*-values were adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate (FDR) procedure.

Crop rotation sequences of the trial area

The trial tested three cropping systems as treatments with different levels of crop diversity, which are:

System 1 (Treatment 1) - low diversity: wheat/ canola/ wheat/ legume cover/ wheat/ wheat/ canola/ grass cover/ wheat/ canola.

System 2 (Treatment 2) – more diversity: wheat/ faba beans/ legume cover/ wheat/ wheat/ canola/ grass cover/ vetch/ wheat

System 3 (Treatment 3) – most diversity: oats/ linseed/ wheat/ legume cover/ wheat/ barley/ canola/ grass cover/ faba beans/ wheat

The one hundred and twenty (120) plots were allocated to accommodate the 4 replicates of the trial as depicted in Figure 2. Of the four replicates, three were randomly assigned to camps 20 and 19C, while replicate 4 for all sequences was allocated to camp 19B. In this manner, the results of the experiment may be analyzed with either 3 or 4 replications. To assess the variability in production, the whole trial area was planted to wheat as a uniformity trial in the year 2015, and for the other years, crops were rotated as shown in Table 1. The crop sequence was recorded annually from 2015 to 2019. In contrast, the NIR spectra and

bulk-density measurements analysed in the present study were obtained only at the 2015 baseline and 2019 endpoint; 2016–2018 therefore represent management history rather than intermediate soil measurements.

Table 1. *Crop rotation sequences over the years of the field trial at Langgewens research farm.*

Crop Sequence	2015	2016	2017	2018	2019
1.	Wheat	Wheat	Legume cover	Wheat	Barley
2.	Wheat	Legume cover	Wheat	Barley	Canola
3.	Wheat	Wheat	Canola	Wheat	Canola
4.	Wheat	Canola	Grass cover	Wheat	Canola
5.	Wheat	Legume cover	Wheat	Wheat	Canola
6.	Wheat	Legume Cover	Wheat	Wheat	Canola
7.	Wheat	Barley	Canola	Grass cover	Faba beans
8.	Wheat	Vetch	Wheat	Wheat	Faba beans
9.	Wheat	Wheat	Barley	Canola	Grass cover
10.	Wheat	Wheat	Wheat	Canola	Grass cover
11.	Wheat	Wheat	Wheat	Canola	Grass cover
12.	Wheat	Wheat	Canola	Wheat	Legume cover
13.	Wheat	Wheat	Faba beans	Wheat	Legume cover
14.	Wheat	Oats	Linseed	Wheat	Legume cover
15.	Wheat	Faba beans	Wheat	Oats	Linseed
16.	Wheat	Grass Cover	Faba beans	Wheat	Oats
17.	Wheat	Wheat	Canola	Grass cover	Vetch
18.	Wheat	Canola	Wheat	Canola	Wheat
19.	Wheat	Grass cover	Wheat	Canola	Wheat
20.	Wheat	Canola	Grass cover	Faba beans	Wheat
21.	Wheat	Wheat	Wheat	Faba beans	Wheat
22.	Wheat	Wheat	Canola	Grass cover	Wheat
23.	Wheat	Canola	Wheat	Legume cover	Wheat
24.	Wheat	Faba beans	Wheat	Legume cover	Wheat
25.	Wheat	Linseed	Wheat	Legume cover	Wheat
26.	Wheat	Wheat	Oats	Linseed	Wheat
27.	Wheat	Canola	Grass Cover	Vetch	Wheat
28.	Wheat	Wheat	Legume cover	Wheat	Wheat
29.	Wheat	Wheat	Legume cover	Wheat	Wheat
30.	Wheat	Grass cover	Vetch	Wheat	Wheat

Results

Inspecting total NIR absorbance

To assess the net change between the baseline and endpoint, the NIR absorbance spectra measured in 2015 and 2019 were plotted on the same axis (Figure 4). Overall, NIR absorbance values recorded in 2019 were higher than those from 2015 for most plots. The reported mean and standard deviation describe the distribution of the calculated spectral

summary across the observations; these statistics should be interpreted as descriptive rather than as evidence of a temporal trajectory. The plot-level t-test gave $p = 5.76781 \times 10^{-9}$, indicating a statistically significant difference between the two sampling dates under the original analysis.

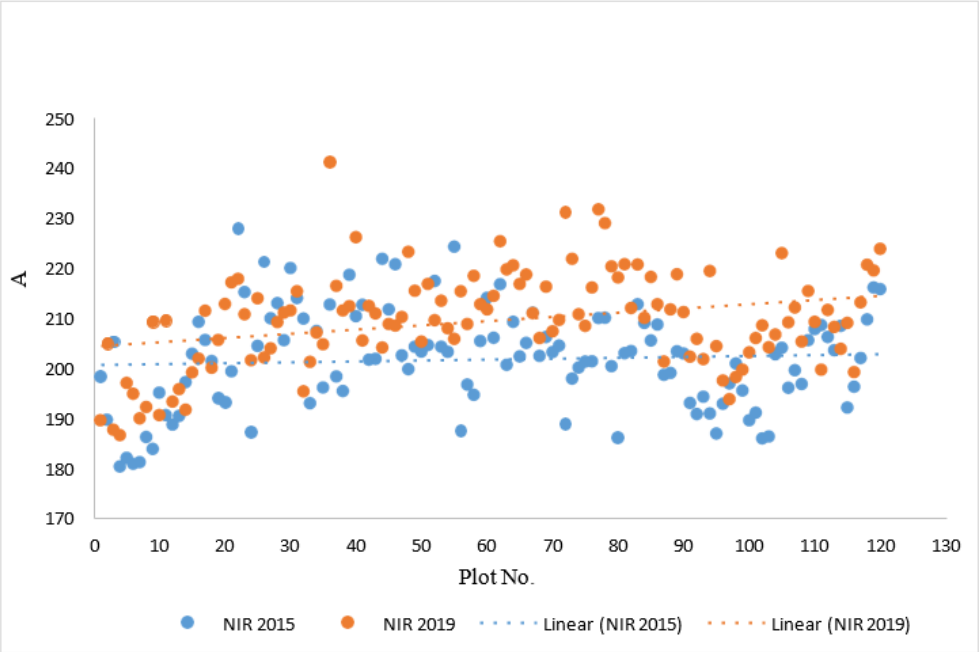


Figure 4. *Summed NIR absorbance index (A) measured across the experimental plots, comparing spectral values obtained at the 2015 baseline and 2019 endpoint.*

Analysis of NIR absorbance per bandwidth and per treatment

This section evaluates whether the spectral differences between 2015 and 2019 were consistent across the measured wavenumbers and how the magnitude of the spectral change varied among the rotation-treatment groups. The observed differences may reflect changes in soil composition and other factors associated with the management history between the two sampling dates.

Band-wise t-tests were performed for each of the 649 measured spectral bands. The unadjusted analysis yielded p-values below 0.05 across the reported bands. The change in absorbance (ΔA) was defined as the 2019 absorbance minus the 2015 absorbance at each wavenumber. The plots were grouped according to their assigned rotation-treatment group, and the mean ΔA was calculated for each group and wavenumber.

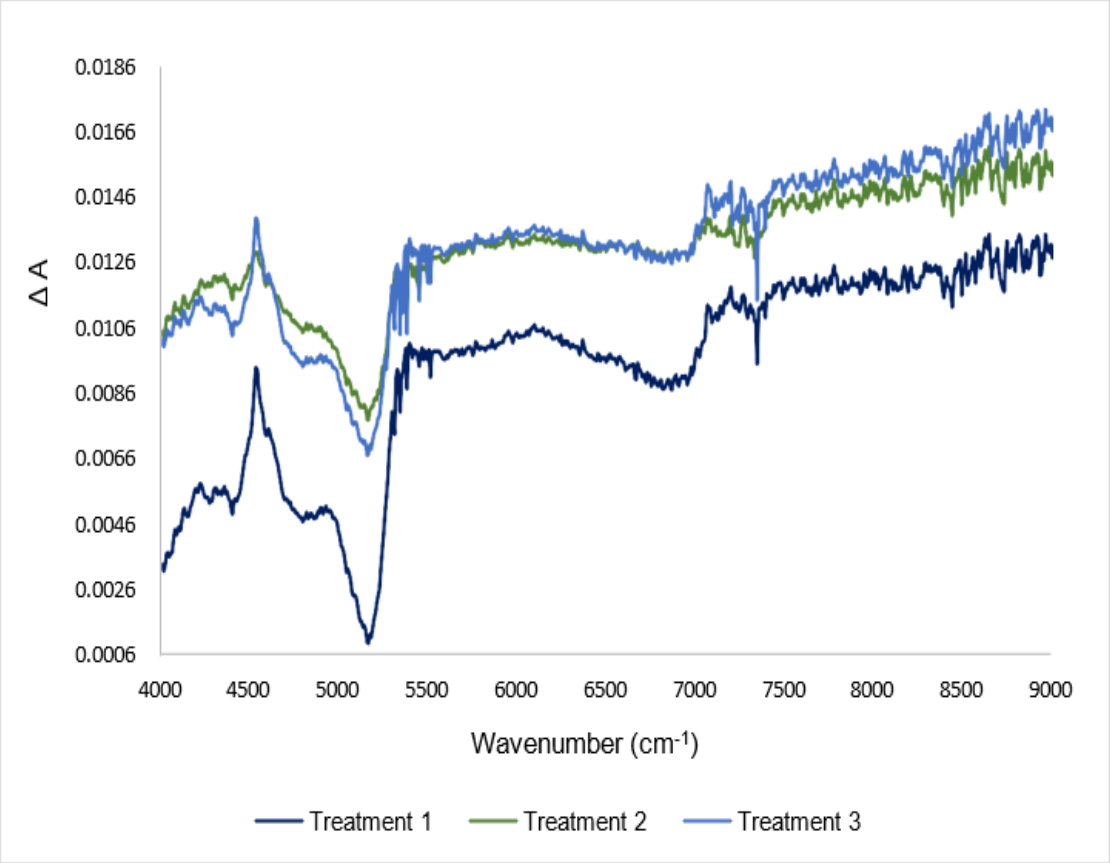


Figure 5. *Mean change in absorbance (ΔA = 2019 − 2015) for each treatment group across the measured wavenumbers. Values are averaged across plots within each treatment group.*

Figure 5 shows that Treatments 2 and 3 generally exhibited higher mean ΔA values and followed similar spectral trends, whereas Treatment 1 showed lower values. Pairwise comparisons between treatment groups are presented in Table 2. For the full spectral summary, Treatment 1 differed from Treatments 2 and 3, while the overall comparison between Treatments 2 and 3 was not significant ($p = 0.15$). For the selected 5160 - 4004 cm^{-1} bands, however, the Treatment 2 versus Treatment 3 comparison was significant ($p = 0.009$). Thus, the full-spectrum and selected-band analyses give different results for this comparison and should not be conflated.

To further examine the spectral region with the greatest variability, bands within 5160 - 4004 cm^{-1} were considered separately. The selected-band comparisons retained the big differences between Treatment 1 and Treatments 2 and 3, while the Treatment 2 versus Treatment 3 comparison became statistically significant ($p = 0.009$), in contrast to the full-spectrum comparison ($p = 0.15$).

Table 2. *Pairwise comparisons of treatment-group spectral responses, showing p-values for the full spectral summary and for the selected 5160–4004 cm⁻¹ bands.*

Treatment	Full spectral summary p-value	Selected bands p-value
1 vs 2	**7.2×10^{-95}**	**4.2×10^{-47}**
1 vs 3	**3.8×10^{-114}**	**1.9×10^{-38}**
2 vs 3	0.15	0.009

Assessment of variations in soil bulk density

Changes in soil bulk density (ρb) were assessed between the 2015 baseline and 2019 endpoint. Figure 6 presents bulk-density measurements for the 120 experimental plots at the two sampling dates. The west–east trend lines for the two years were broadly parallel. Overall, bulk density decreased across the study area, with the 2019 trend line lying below that of 2015. The mean bulk density decreased from 1.36 g cm^{-3} in 2015 to 1.23 g cm^{-3} in 2019. This reduction is consistent with a lower degree of soil compaction, but porosity, pore-size distribution, aeration, and infiltration were not directly measured and therefore cannot be inferred as direct responses from bulk density alone.

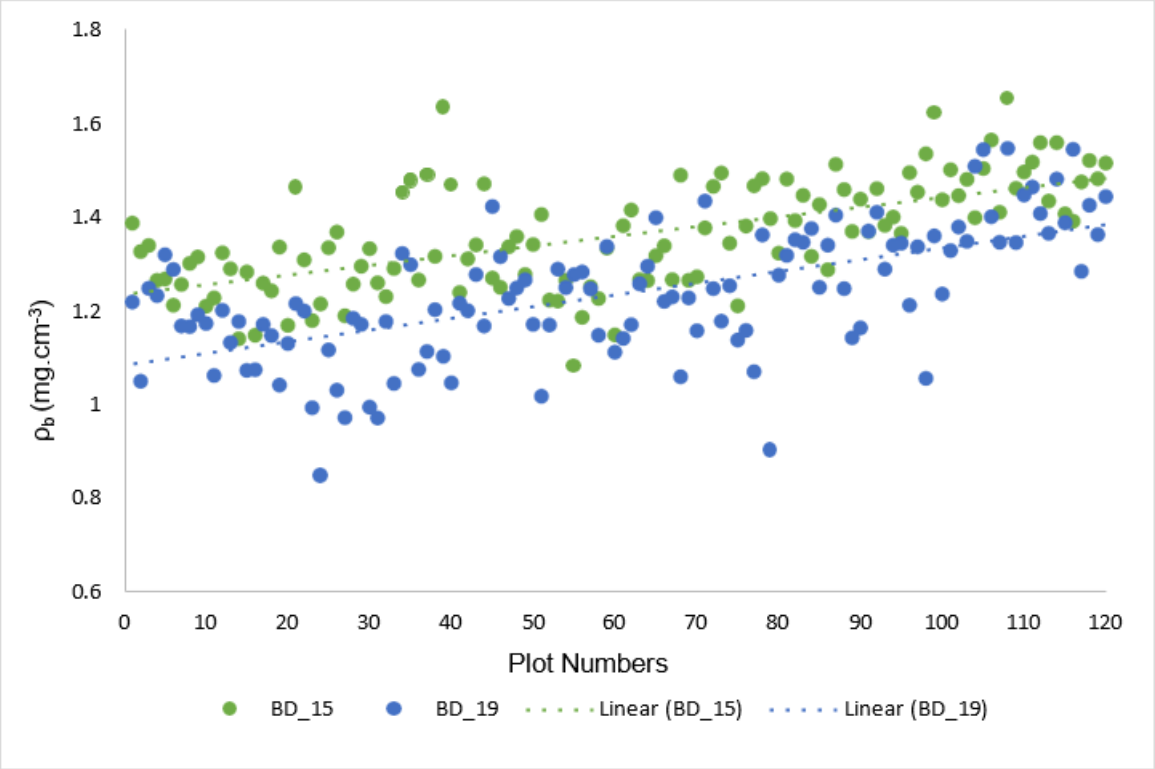


Figure 6. *Soil bulk-density values across the experimental plots at the 2015 baseline and 2019 endpoint, expressed in g cm^{-3}.*

Figure 7 illustrates bulk-density values for the three rotation-treatment groups. Mean bulk density was lower in 2019 than in 2015 for all three groups. The t-test results are presented in Table 3. The treatment-level means show the largest numerical reduction for T

reatment 3, followed by Treatment 2 and Treatment 1; this pattern describes an association and does not by itself establish a causal effect of crop diversity.

Figure 7. Mean soil bulk density at the 2015 baseline and 2019 endpoint grouped by rotation-treatment group, with standard error bars.

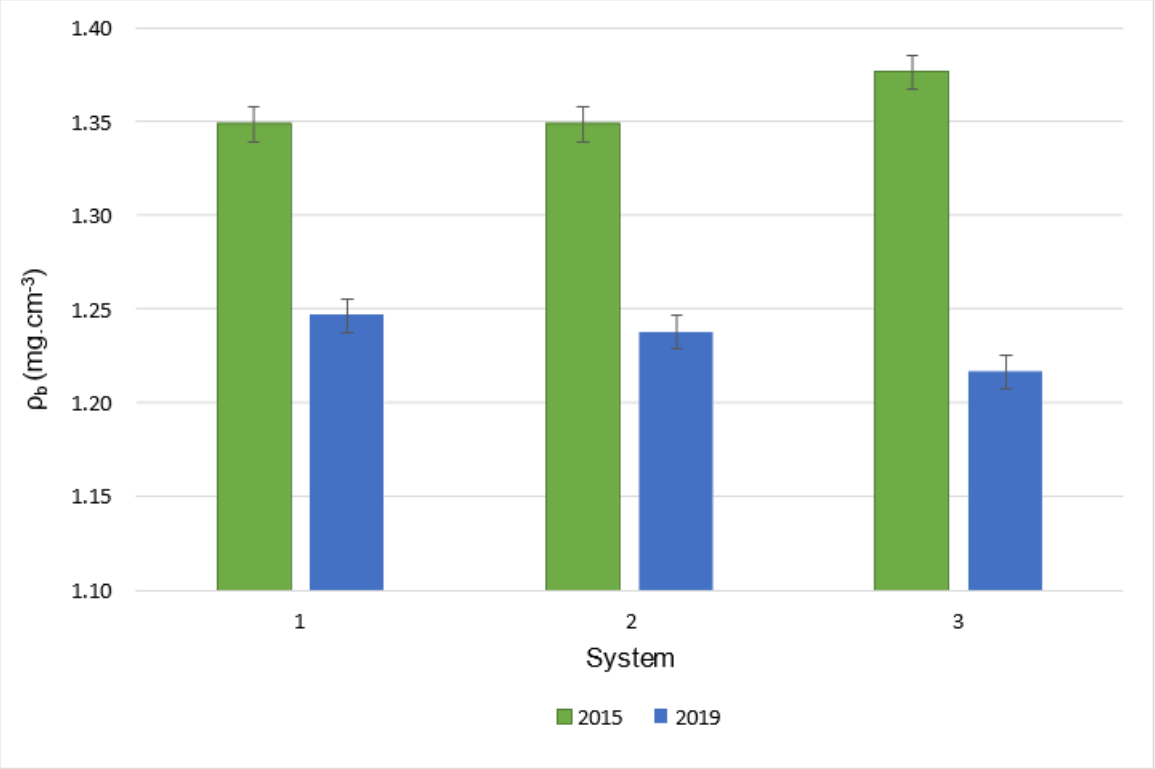


Figure 7. *Average soil bulk density for the years 2015 and 2019 grouped by system (treatment), with standard error bars.*

Table 3. *Descriptive statistics for soil bulk density at the 2015 baseline and 2019 endpoint and the corresponding t-test results.*

System	Average		σ		St. Error		p-value
Year	2015 (g cm^{-3})	2019 (g cm^{-3})	**2015**	**2019**	**2015**	**2019**	
System 1	1.35	1.25	0.11	0.13	0.02	0.02	$9.7x10^{-6}$
System 2	1.35	1.24	0.11	0.13	0.02	0.02	$2.2x10^{-6}$
System 3	1.38	1.22	0.13	0.16	0.02	0.02	$1.4x10^{-7}$

Table 4 summarises the net change in bulk density for each crop sequence between the 2015 baseline and the 2019 endpoint. Here, $\Delta\rho b = \rho b,2019 - \rho b, 2015$; negative values therefore indicate a reduction in bulk density. The 30 crop sequences represent management histories rather than 30 independent treatments. The original sequence-level p-values were adjusted using the Benjamini–Hochberg false-discovery-rate procedure; after adjustment, none of the 30 sequence comparisons remained significant at $\alpha = 0.05$.

Table 4. *Change in soil bulk density between the 2015 baseline and the 2019 final sampling following the 2016–2019 crop sequences.*

Crop Sequence					Δρb	σ	P-value	BH q-value
1.	Wheat	Legume cover	Wheat	Barley	-0.17	0.11	**0.049**	0.191
2.	Legume cover	Wheat	Barley	Canola	-0.15	0.07	**0.021**	0.162
3.	Wheat	Canola	Wheat	Canola	-0.04	0.17	0.707	0.781
4.	Canola	Grass cover	Wheat	Canola	-0.1	0.11	0.155	0.245
5.	Legume cover	Wheat	Wheat	Canola	-0.11	0.08	**0.064**	0.191
6.	Legume Cover	Wheat	Wheat	Canola	-0.02	0.12	0.842	0.842
7.	Barley	Canola	Grass cover	Faba beans	-0.34	0.17	**0.027**	0.162
8.	Vetch	Wheat	Wheat	Faba beans	-0.11	0.09	**0.089**	0.191
9.	Wheat	Barley	Canola	Grass cover	-0.13	0.12	0.115	0.203
10.	Wheat	Wheat	Canola	Grass cover	-0.12	0.13	0.166	0.249
11.	Wheat	Wheat	Canola	Grass cover	-0.19	0.09	**0.025**	0.162
12.	Wheat	Canola	Wheat	Legume cover	-0.05	0.05	0.141	0.235
13.	Wheat	Faba beans	Wheat	Legume cover	-0.1	0.14	0.232	0.316
14.	Oats	Linseed	Wheat	Legume cover	-0.08	0.18	0.437	0.516
15.	Faba beans	Wheat	Oats	Linseed	-0.24	0.19	**0.082**	0.191
16.	Grass Cover	Faba beans	Wheat	Oats	-0.17	0.04	**0.002**	0.060
17.	Wheat	Canola	Grass cover	Vetch	-0.14	0.17	0.205	0.293
18.	Canola	Wheat	Canola	Wheat	-0.1	0.03	**0.009**	0.135
19.	Grass cover	Wheat	Canola	Wheat	-0.15	0.1	**0.061**	0.191
20.	Canola	Grass cover	Faba beans	Wheat	-0.02	0.17	0.819	0.842
21.	Wheat	Wheat	Faba beans	Wheat	-0.15	0.12	**0.084**	0.191
22.	Wheat	Canola	Grass cover	Wheat	-0.09	0.15	0.305	0.381
23.	Canola	Wheat	Legume cover	Wheat	-0.12	0.1	**0.077**	0.191
24.	Faba beans	Wheat	Legume cover	Wheat	0.03	0.07	0.447	0.516
25.	Linseed	Wheat	Legume cover	Wheat	-0.18	0.28	0.298	0.381
26.	Wheat	Oats	Linseed	Wheat	-0.16	0.13	**0.096**	0.192
27.	Canola	Grass Cover	Vetch	Wheat	-0.25	0.2	**0.089**	0.191
28.	Wheat	Legume cover	Wheat	Wheat	0.02	0.1	0.729	0.781
29.	Wheat	Legume cover	Wheat	Wheat	-0.22	0.19	0.104	0.195
30.	Grass cover	Vetch	Wheat	Wheat	-0.2	0.11	**0.033**	0.165

Soil organic carbon

Soil organic carbon (SOC) plays an important role in mitigating greenhouse gas emissions, sustaining and improving agricultural production, and enhancing soil quality (Paustian et al., 2019). Changes in SOC over the trial period were assessed by comparing SOC measurements obtained in 2015 and 2019 (Figure 8). Across all three systems, SOC concentrations were lower in 2019 than in 2015, indicating an overall decline in SOC over the trial period. The mean reduction in SOC across the three systems was approximately 0.16 percentage points. A paired-samples t-test indicated that the difference between SOC measurements in 2015 and 2019 was statistically significant ($p < 0.05$).

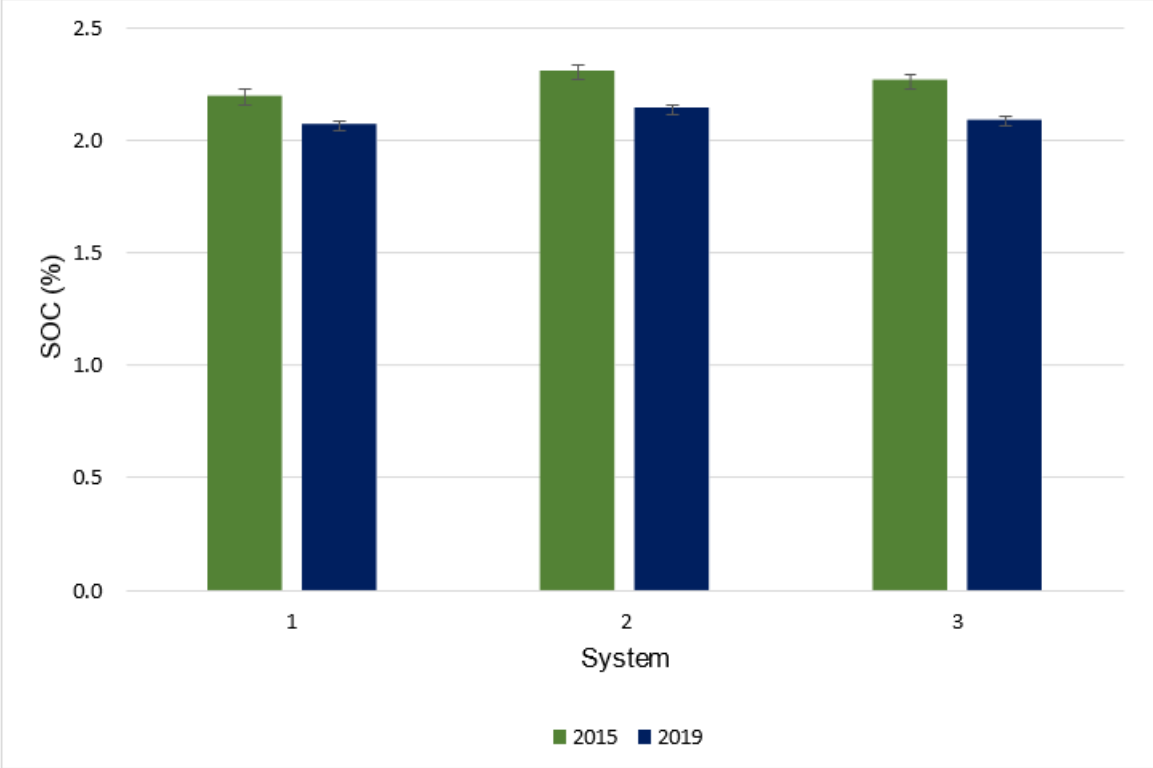


Figure 8. *Soil organic carbon (SOC) for the years 2015 and 2019, averages grouped per system (treatment) with standard error bars.*

Discussion

Changes in NIR absorbance, soil organic carbon and bulk density under rotationcrop

An upward shift in the measured spectra was observed in Figure 4, with higher NIR absorbance in 2019 than in 2015, indicating a change in the spectral characteristics of the prepared soil samples. Soil NIR spectra reflect the combined influence of organic carbon and other organic compounds, mineralogical composition, iron-bearing minerals, and O–H-, C–H-, and N–H-containing compounds (Chang et al., 2001; Stenberg et al., 2010; Bai et al., 2022). Although SOC contributes to soil spectral characteristics and can be estimated using Vis–NIR

spectroscopy (Soriano-Disla et al., 2014; Bushong et al., 2015; Bai et al., 2022; Reyes and Ließ, 2024), the mean SOC change in the present study was approximately - 0.16 between 2015 and 2019. Therefore, the higher NIR absorbance cannot be interpreted as evidence of increased SOC and may instead reflect changes in other spectrally active constituents or their combined effects.

Treatments 2 and 3 exhibited higher mean ΔA values than Treatment 1 (Figure 5), indicating an association between rotation history and spectral response. Crop diversification can modify biomass production, root turnover, and residue inputs, which may alter soil chemical and physical characteristics over time (Kazemi et al., 2023; Li et al., 2024; Kundu et al., 2025). Such cumulative changes may contribute to differences in spectral response among rotation treatments, although the contribution of individual soil constituents cannot be separated using the present spectral data.

Bulk density decreased across all three rotation treatments between 2015 and 2019, with p-values of 9.7×10^{-6}, 2.2×10^{-6} and 1.4×10^{-7} for treatments 1, 2 and 3, respectively. The mean bulk density in 2019 was 1.255 g cm^{-3}. The consistent decline indicates reduced soil packing over the four years and is plausibly associated with cumulative effects of crop growth and rotation. Repeated root growth and turnover can rearrange soil particles and create biopores that provide pathways for air and water movement (Ankit et al., 2024). Residue decomposition and biological activity may further promote aggregation and pore development, reducing particle packing and contributing to lower bulk density (Gupta et al., 2024; Ferreira et al., 2024; Duan et al., 2026). These processes provide a plausible explanation for the observed temporal decline in bulk density under continued crop rotation.

Most of the 30 crop sequences also showed a numerical decline in bulk density, although sequence 24 showed a small increase. This widespread direction of change indicates that the reduction was not restricted to a single treatment. The magnitude differed among sequences, suggesting that crop composition and associated rooting and residue characteristics may have influenced the extent of structural change. Treatment 3 showed the greatest numerical reduction, consistent with a potentially stronger cumulative influence of its rotation sequence on soil structure. However, after Benjamini–Hochberg adjustment, none of the 30 sequence-level comparisons remained significant at $\alpha = 0.05$; therefore, individual sequence differences should be interpreted as patterns rather than independent causal effects.

The concurrent decline in SOC and bulk density indicates that the reduction in bulk density was not simply associated with increasing SOC. Instead, it is more consistent with interacting physical and biological processes, including root penetration and turnover, biopore formation, residue decomposition, aggregation, and changes in particle arrangement. Soil structural changes can therefore occur independently of short-term changes in SOC concentration.

The contrasting trends in NIR absorbance, SOC, and bulk density provide an important integrated interpretation of the results. From 2015 to 2019, NIR absorbance increased, whereas both SOC and bulk density decreased. Because the NIR samples were dried and ground before scanning, the spectral measurements represent the characteristics of the prepared soil material and do not retain the intact field pore structure. Thus, the NIR and bulk-density measurements provide complementary information: NIR characterises

differences in the spectral properties of the soil material, whereas bulk density reflects changes in field soil packing.

The decline in bulk density across the rotation treatments is consistent with cumulative changes associated with crop growth, root activity, residue decomposition, and soil structural development. The greater reduction under Treatment 3 suggests that rotation composition may have influenced the magnitude of these changes. However, the concurrent decline in SOC demonstrates that the reduction in bulk density cannot be attributed to SOC accumulation alone. The findings therefore indicate that crop rotation was associated with changes in both the spectral and physical characteristics of the soil, while the contrasting responses of NIR absorbance, SOC, and bulk density demonstrate the need to interpret spectral measurements alongside independently measured soil properties.

Conclusion

This study evaluated changes in NIR spectral absorbance, soil organic carbon (SOC), and bulk density between a common 2015 baseline and a 2019 endpoint following four years of contrasting crop-rotation management. NIR absorbance increased over the study period, with Treatments 2 and 3 generally showing higher mean ΔA values than Treatment 1. However, SOC declined by approximately 0.16 on average, indicating that the increase in NIR absorbance should not be interpreted as increased SOC.

Bulk density decreased across all three treatments, with the greatest numerical reduction occurring in Treatment 3. This decline occurred alongside decreasing SOC and is consistent with changes in soil packing associated with crop growth, root activity, residue decomposition, and related structural processes.

Contrasting crop rotations were associated with changes in NIR spectral response and bulk density, while SOC declined. The results highlight the importance of interpreting NIR spectra using multiple independently measured soil properties rather than as a direct proxy for a single soil attribute. Further studies should incorporate repeated sampling and direct measurements of soil structural and biological properties to better establish the mechanisms underlying these changes.

Conflict of interest

The authors declare no potential conflict of interest.

Acknowledgments

The authors gratefully acknowledge Citrus Academy, South Africa, for financial support of this study, and the Department of Agriculture, Western Cape, South Africa, for funding the laboratory analyses. Special thanks are extended to Devin Osborne for conducting the 2015 NIR scans and to Lisa Rubin for her assistance with the 2019 fieldwork.

References

Ankit, Prakash, D., Sheoran, S., Yadav, P. K., Raj, D., Rachna, Gupta, R. K., El-Hendawy, S., Mattar, M. A. (2024). Sustainable cropping sequences to improve soil fertility and microbiological properties. *Sustainability*, 16(22), 9821.

Ashworth, A. J., Owens, P. R., Allen, F. L. (2020). Long-term cropping systems management influences soil strength and nutrient cycling. *Geoderma*, 361.

Bai, Z., Xie, M., Hu, B., Luo, D., Wan, C., Peng, J., & Shi, Z. (2022). Estimation of soil organic carbon using Vis-NIR spectral data and spectral feature bands selection in Southern Xinjiang, China. *Sensors, 22*(16), 6124.

Blanco-Canqui, H., & Ruis, S. J. (2018). No-tillage and soil physical environment. *Geoderma, 326*, 164–200.

Blanchy, G., Bragato, G., Di Bene, C. G., Jarvis, N., Larsbo, M., Meurer, K. H. E., & Garre, S. (2023). Soil and crop management practices and the water regulation functions of soils: A qualitative synthesis of meta-analyses relevant to European agriculture. *SOIL, 9*(1), 1–20.

Bushong, J. T., Norman, R. J., & Slaton, N. A. (2015). Near-infrared reflectance spectroscopy as a method for determining organic carbon concentrations in soil. *Communications in Soil Science and Plant Analysis, 46*, 1791–1801.

Chang, C., Laird, D. A., Mausbach, M. J., & Hurburgh, C. R. (2001). Near-infrared reflectance spectroscopy–principal components regression analyses of soil properties. *Soil Science Society of America Journal, 65*, 480–490.

Dhillon, M. S., Koellner, T., Asam, S., Bogenreuther, J., Dech, S., Gessner, U., Gruschwitz, D., Annuth, S. H., Kraus, T., Rummler, T., Schaefer, C., Schönbrodt-Stitt, S., Steffan-Dewenter, I., Wilde, M., & Ullmann, T. (2025). Landscape structure, climate variability, and soil quality shape crop biomass patterns in agricultural ecosystems of Bavaria. *Frontiers in Plant Science, 16*, 1630087.

Duan, Y., Zhang, H., He, C., Gao, G., & Tang, Q. (2026). Effects of different rotation crops on soil physicochemical properties and microbial community structure in continuous cotton fields. *Frontiers in Microbiology, 17*, 1740768.

Ferreira, A. O., Sá, J. C. M., Lal, R., Barth, G., Inagaki, T. M., Gonçalves, D. P., Briedis, C., Tivet, A. R., & da Silva, W. R. (2024). Why no-till system sequesters more carbon and is more resilient and productive with contrasting fertilization regimes in a highly weathered soil? *Soil and Tillage Research, 244*.

Gupta, R. K., Sraw, P. K., Kang, J. S., Kaur, J., Sharma, V., Pathania, N., Kalia, A., Al-Ansari, N., Alataway, A., Dewidar, A. Z., & Mattar, M. A. (2024). Interactive effects of long-term management of crop residue and phosphorus fertilization on wheat productivity and soil health in the rice–wheat system. *Scientific Reports, 14*.

Håkansson, I., & Lipiec, J. (2000). A review of the usefulness of relative bulk density values in studies of soil structure and compaction. *Soil and Tillage Research, 53*(2), 71–85.

Jakšić, S., Ninkov, J., Milić, S., Vasin, J., Živanov, M., Perović, V., Banjac, B., Vučković, S., Dozet, G., & Komlen, V. (2021). Topographic position, land use and soil management effects on soil organic carbon (Vineyard region of Niš, Serbia). *Agronomy, 11*(7), 1438.

Kazemi Garajeh, M., Hassangholizadeh, K., Bakhshi Lomer, A. R., Ranjbari, A., Ebadi, L., & Sadeghnejad, M. (2023). Monitoring the impacts of crop residue cover on agricultural productivity and soil chemical and physical characteristics. *Scientific Reports, 13*(1), 15054.

Kundu, A., Sarkar, J. D., Mukherjee, S., Nandi, R. R., Saha, S., Bandyopadhyay, P. K., & Sharma, S. (2025). Impact of different cropping systems on structural attributes and aggregate-associated carbon dynamics of clayey soil under conservation agriculture. *Frontiers*

in Sustainable Food Systems, 9, 1622985.

Katuwal, S., Knadel, M., Norgaard, T., Moldrup, P., Greve, M. H., & de Jonge, L. W. (2020). Predicting the dry bulk density of soils across Denmark: Comparison of single-parameter, multi-parameter, and Vis–NIR based models. *Geoderma, 361*, 114080.

Li, G., Yu, G., Shen, P., Hou, Y., Ren, Z., Li, N., Liao, Y., Li, T., & Wen, X. (2024). Crop diversification promotes soil aggregation and carbon accumulation in global agroecosystems: A meta-analysis. *Journal of Environmental Management*.

Ma, Y. Y., Lei, T. W., Zhang, X. P., & Chen, Y. X. (2013). Volume replacement method for direct measurement of soil moisture and bulk density. *Transactions of the Chinese Society of Agricultural Engineering, 29*(9), 86–93.

McBratney, A. B., Mendonça Santos, M. L., & Minasny, B. (2003). On digital soil mapping. *Geoderma, 117*(1–2), 3–52.

Mtyobile, M., Muzangwa, L., & Mnkeni, P. N. S. (2020). Tillage and crop rotation effects on soil carbon and selected soil physical properties in a Haplic Cambisol in Eastern Cape, South Africa. *Soil and Water Research, 15*(1), 47–54.

Ngejane, N., Rozanov, A., Clarke, C., & Strauss, J. (2026). Spatial prediction of soil properties and wheat yield variability at farm scale using soil near-infrared spectral signatures. *African Journal of Agricultural Research*, 22(6), 408-418.

Non-affiliated Soil Analysis Work Committee (1990). Handbook of standard soil testing methods for advisory purposes. Pretoria: Soil Science Society of South Africa.

Nunes, M. R., Karlen, D. L., & Moorman, T. B. (2020). Tillage intensity effects on soil structure indicators: A US meta-analysis. *Sustainability, 12*(5), 2071.

Orzech, K., Wanic, M., & Załuski, D. (2021). The effects of soil compaction and different tillage systems on the bulk density and moisture content of soil and the yields of winter oilseed rape and cereals. *Agriculture, 11*(7), 666.

Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C sequestration as a biological negative emission strategy. *Frontiers in Climate, 1*, 8.

Poggio, L., de Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., & Rossiter, D. (2021). SoilGrids 2.0: Producing soil information for the globe with quantified spatial uncertainty. *SOIL, 7*(1), 217–240.

Reyes, J., & Ließ, M. (2024). Spectral data processing for field-scale soil organic carbon monitoring. *Sensors, 24*(3), 849.

Rigon, J. P. G., & Calonego, J. C. (2020). Soil carbon fluxes and balances of crop rotations under long-term no-till. *Carbon Balance and Management, 15*, 19.

Shin, S. K., Lee, S. J., & Park, J. H. (2025). Prediction of soil properties using VIS-NIR spectroscopy combined with machine learning: A review. *Sensors, 25*(16), 5045.

Soriano-Disla, J. M., Janik, L. J., Rossel, R. A. V., MacDonald, L. M., & McLaughlin, M. J. (2014). The performance of visible, near-, and mid-infrared reflectance spectroscopy for prediction of soil physical, chemical, and biological properties. *Applied Spectroscopy Reviews, 49*(2), 139

Stenberg, B., Rossel, R. A. V., Mouazen, A. M., & Wetterlind, J. (2010). Visible and near infrared spectroscopy in soil science. *Advances in Agronomy, 107*, 163–215.

USDA Natural Resources Conservation Service. (2022). *Soil bulk density/moisture/aeration: Soil quality indicators guide*. United States Department of

Agriculture.

Védère, C., Lebrun, M., Honvault, N., Aubertin, M., Girardin, C., Garnier, P., Dignac, M. F., Houben, D., & Rumpel, C. (2022). How does soil water status influence the fate of soil organic matter? A review of processes across scales. *Earth-Science Reviews, 234*, 104225.

Wang, C., Zhang, G., Zhu, P., Chen, S., & Wan, Y. (2023). Spatial variation of soil functions affected by land use type and slope position in agricultural small watershed. *Catena, 225*, 106972.

Wang, Z., Wu, W., & Liu, H. (2024). Spatial estimation of soil organic carbon content utilizing PlanetScope, Sentinel-2, and Sentinel-1 data. *Remote Sensing*, *16*(17), 3268.

Win, A., Minasny, B., Ringrose-Voase, A., & Jang, H. (2025). Improving the accuracy of digital soil mapping using remote sensing and topography covariates in the Central Dry Zone of Myanmar. *Geoderma, 442*, 117058.

Xu, C., Liu, W., Li, J., Wu, J., Zhou, Y., & Kader, R. (2024). Dynamic change of soil aggregate stability and infiltration properties during crop growth under four tillage measures in Mollisols region of northeast China. *Frontiers in Earth Science, 12*, 1357467.

Yaqoob, N., Malekian, R., Farooque, A. A., Harder, P., Esau, T. J., Zaman, Q. U., Hu, Y., &

Dwyer, R. (2024). Topography-driven variability in soil greenhouse gas emissions during potato growth season. *Soil Use and Management*, *40*(4), e13042.